SMALL EFFICIENT THERMOPHOTOVOLTAIC POWER SUPPLY USING INFRARED-SENSITIVE GALLIUM ANTIMONIDE CELLS

ARMY STTR PHASE II FINAL REPORT

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AUGUST 11, 1999

U.S. ARMY RESEARCH OFFICE

CONTRACT NUMBER DAAG55-97-C-0002

JX CRYSTALS INC.

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Summary:

The goal of this contract was to fabricate and deliver a cylindrical 150 W TPV generator complete with a GaSb photovoltaic converter array (PCA) and a propane fired burner / emitter / recuperator (BER). In the following pages, we summarize the progress made toward this goal, the primary problem encountered, a solution to this problem, validation of the solution, and our future plans under a newly issued Army Research Office contract. A detailed presentation on the work done under this contract was given to Army review personnel on June 29, 1999 and that presentation is attached hereto as an appendix.

Progress:

In order to build the proposed TPV generator, it was necessary to build both a photovoltaic converter assembly complete with air cooling system and a burner / emitter / recuperator system complete with propane and air delivery systems and igniter. These two subsystems were designed and built in parallel and then combined subsequently near the end of the program in order to fabricate the delivered TPV generator.

The project began with the fabrication of the PCA shown conceptually in VG # 5. A PCA consisted of 12 circuits with each circuit containing 30 GaSb cells. The circuit and circuit design is shown in VG # 6. We actually fabricated three live PCAs over the course of this contract. The first one (VG #10) was fabricated specifically for testing with an electrically heated SiC globar. The next two PCAs (VG # 11 & 12) were fabricated for use with propane burners, one for delivery and the last one to remain here for future testing and improvement. Forty circuits including spares were fabricated and tested with generally excellent performance (VGs # 7, 8, & 9). The first PCA was tested both with 200 cfm and 380 cfm of cooling air. With 380 cfm of cooling, it produced 540 W of electric power output (VG #15). With 200 cfm, cooling was adequate for up to 150 W of electric power out and 5 kW of heat load (circuit temperature = 90 C).

The burner / emitter / recuperator work proceeded in parallel with the PCA work and is described in VGs # 17 through 21. We were able to operate the burner at 6 lpm of propane. This corresponded to approximately 7.5 kW of input fuel energy.

We then combined the PCA and BER in order to make a complete TPV generator and measured the PCA output. We actually wired the circuits in the PCA in pairs so that we measured the outputs of the six pairs. The best output power achieved was 135 W at an estimated array heat load of approximately 5 kW. The results for this test are summarized in VGs 22 & 23. Note that the SiC emitter temperature averaged about 1150 C.

Problem:

The final array output was lower than we had hoped. One can state this problem in two ways. One can simply note that the overall conversion efficiency was very low. In fact, the PCA conversion efficiency was 150/5000 = 3%. However, it is more useful to state this problem differently as follows.

The TPV problem is simply a three-step energy transfer problem. One must first burn a fuel and transfer the energy in the hot combustion gases to the IR emitter surface. Then one needs to transfer the energy from the emitter to cells, and finally one needs to remove the waste heat from the cells.

In the previous section, we noted that we were able to transfer approximately 5 kW to the emitter and that we could remove approximately this amount as waste heat from the cells. We note that the emitter area is approximately 500 cm2. This means that the heat flux leaving the emitter arriving at the cells was approximately 10 W/cm2. An analysis of the terms associated with this emitter-to-cell heat transfer process reveals both the efficiency problem and its solution.

Heat is transferred from the emitter to the cells in three ways, by radiation, by conduction, and by convection. Our assumption at the beginning of this contract was that radiation was dominant. Given radiation, we proposed to use filters to tailor the spectrum to allow the useful shorter cell-convertible wavelengths through to the cells while reflecting the non-convertible longer wavelength energy back to the emitter. Our target emitter temperature at that time was 1400 C. At that temperature, 25% of the radiant energy would be within the cell convertible band with wavelengths less than 1.8 microns, 50% would be within a dielectric filter reflection band of 1.8 to 3.6 microns, and the remaining longer wavelength energy would only be 25% of the total. So we could handle 75% of the radiant energy effectively.

At this point, our perspective has changed. We now believe that for an emitter temperature of 1100 C, the conduction and convection terms account for a heat flux of about 3 W/cm2. And unfortunately for a SiC emitter at 1100 C with an emittance of 0.8, 40% of the radiant energy or approximately 6 W/cm2 is beyond 3.5 microns. These two parasitic terms account for 9 W/cm2 from our available budget of 10 W/cm2. So, the problem is that before we can get significant amounts of cell convertible radiant energy, we need to reduce the long wavelength radiant energy and the conduction and convection heat transfer terms. This can be done as is described in the following section.

Solution:

The solution to the TPV emitter problem can be found by analogy with the Edison light bulb. We need to suppress long wavelength radiant energy and it would be desirable to eliminate conduction and convection altogether. While the long wavelength emittance of SiC is actually higher than its short wavelength emittance, the emittance of refractory metals such as tungsten is higher for cell

convertible wavelengths than for longer wavelengths. In other words, the long wavelength energy radiated from refractory metals is suppressed. So the solution to the TPV emitter problem is to coat the SiC emitter with a refractory metal and to surround it with an evacuated glass tube. This can be done as in the emitter thermos shown in the TPV generator in VG # 33. In fact, we can do a little better than an Edison light bulb by coating the refractory metal emitter surface with an antireflection coating centered in the cell convertible band. VG #26 shows the theoretical emittance expected for such an AR coated refractory metal (RM) emitter and the following table shows the projected radiant power distributions for this emitter at 1200, 1300, and 1400 C.

Table 1: Radiant power distribution for AR/RM emitter

Temperature (C)	1200	1300	1400
Power Density (W/cm2)			
0.7 to 1.8 micron	4.6	7.6	10.5
1.8 to 10 micron	2.2	2.9	3.6
0.7 to 10 micron	6.8	10.5	14.1
Spectral Efficiency (%)	67	70	74

Referring now to the 1300 C column in table 1, note that instead of 1 out of 10 W/cm2 being available for cell conversion with the current emitter configuration, we project that 7.6 out of 10.5 W/cm2 should now be convertible with the AR/RM emitter thermos configuration. Assuming a cell conversion efficiency of 30% and if 70% of the radiant power were in-band, then the PCA conversion efficiency would be 21%.

Validation of Solution:

While the AR/RM emitter thermos of VG # 33 still needs to be developed, linear tungsten filament light bulbs are commercially available. Unfortunately, these light bulbs are not identical to an emitter thermos. They run hotter; the tungsten filament is not AR coated; and there is no mid-band filter. However, these differences tend to compensate each other. Furthermore, the TPV emitter thermos and a light bulb do have important similarities. In both cases, the short wavelength emittance is higher than the long wavelength emittance and an evacuated bulb eliminates conduction and convection.

So, we have fitted our third PCA with a tungsten filament light bulb as the IR emitter. This assembly is shown in VG #12. In operation, the light bulb consumed 1.1 kW and the PCA produced 108 W. The measured PCA conversion efficiency was then 10%.

Future:

Although the initial TPV concept is 30 years old, the first high-performance low bandgap GaSb cells were first demonstrated only 10 years ago in 1989. It was just 5 years ago when these cells became available in quantity at JX Crystals. Only recently have these cells been incorporated in arrays in fuel fired TPV generators. BER systems for TPV have only been fabricated within the last couple of years. This report contains the first somewhat complete analysis of the operation of a complete fuel fired TPV generator. This analysis indicates that the parasitic losses associated with conduction, convection, and long wavelength radiation need to be reduced before a substantial amount of radiation can be shifted into the cell convertible wavelength band. This can be done by coating a durable emitter substrate material like SiC first with a refractory metal followed by an antireflection coating tuned to the cell convertible wavelength band. This selective emitter is then heated by combustion from within and surrounded by a evacuated glass bulb to create a selective emitter thermos. This concept is completely new to TPV and is now being funded under a separate Army Research Office contract.

Other Report Requirements:

Report of Inventions) a DD form 882 is included with final report submission. No inventions are reported. This contract furthered development of concepts that were conceived and reduced to practice prior to the contract.

Participating Scientific Personnel) At JX Crystals: Dr. Lewis M. Fraas, James E. Avery, Dr. John Samaras, Dr. William Mulligan, Galen Magendanz and Wilbert Daniels. At Western Washington University: Michaeal Seal and Edward West. No advanced degrees were earned during this project.

Publications and Technical Reports) JX Crystals reported on TPV development at the third and fourth TPV conferences, run by NREL in May of 1997 and October of 1998. Relevant papers are:

1. "Development Status on a TPV Cylinder for Combined Heat and Power for the Home" (1998)
2. Commercial GaSb Cell and Circuit Development for the Midnight Sun® TPV Stove" (1998)
3. "A Single TPV Cell Power Density and Efficiency Measurement Technique" (1998)
4. "Low Cost High Power GaSb Photovoltaic Cells" (1997)
5. "2-Amp TPV Cogenerator Using Forced-Air Cooled GaSb Cells" (1997)
6. "Matched Infrared Emitters for Use with GaSb TPV Cells" (1997)
7. "Status of TPV Commercial System Development Using GaSb Infrared Sensitive Cells", Second World PV Specialists Conference, Vienna, Austria, July 6-10, 1998.

Army STTR II Final Report

Small Efficient TPV Power Supply Using Infrared Sensitive GaSb Cells

P.I. – Lewis M. Fraas

June 29, 1999

JX Crystals Inc.
Midnight Sun®

Outline

- System Design Overview
- Photovoltaic Converter Assembly (PCA)
- Burner-Emitter-Recuperator (BER)
- Complete system
- Spectral control
- Future

Design Goals

	6/96	6/99
■ Fuel Energy Input	2 kW	8 kW
■ Emitter Radiant Output	1.3 kW	5.6 kW
■ Emitter Temperature	1500 C	1430 C
■ PV Array Output	225 W	560 W
■ Net Output	150 W	500 W
■ Net Efficiency	7.5%	6.3%

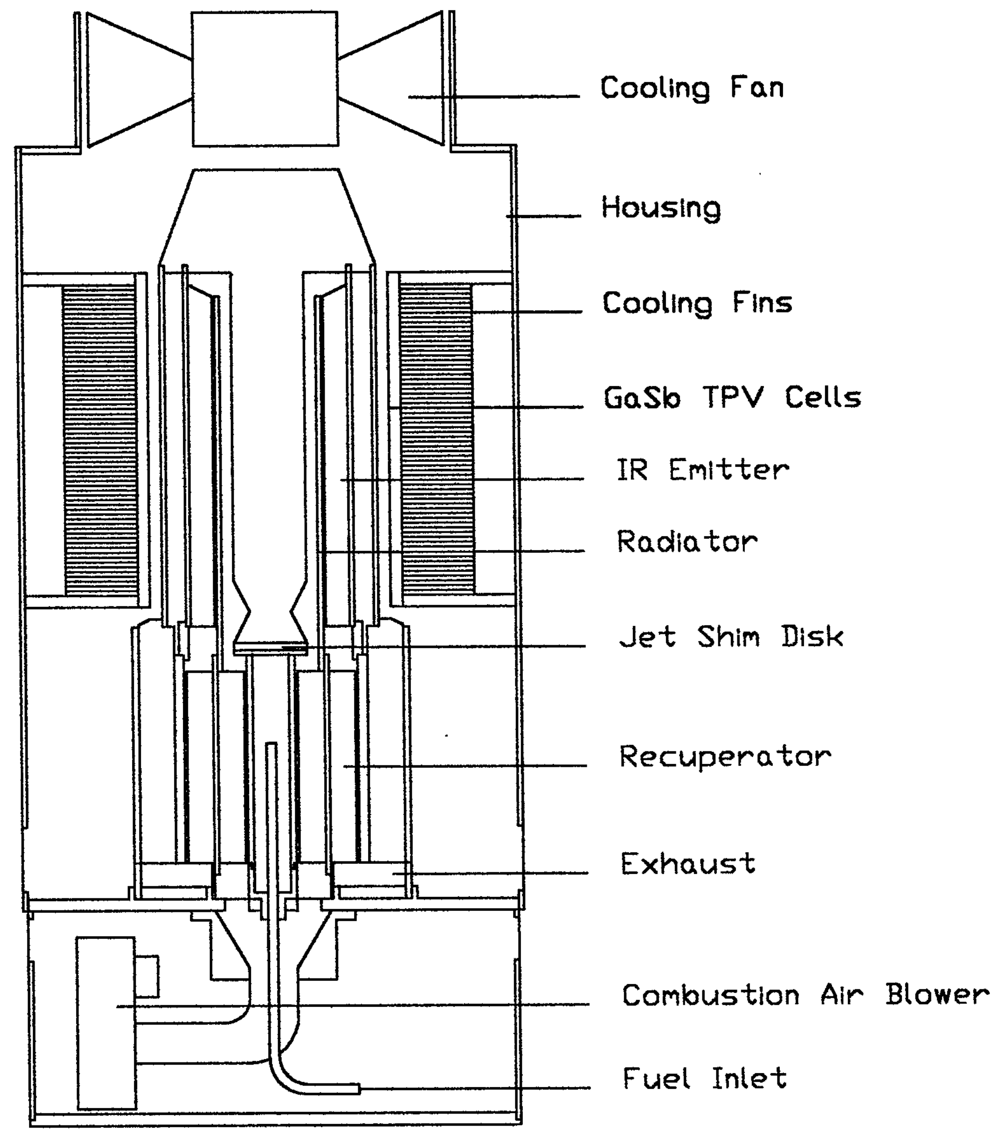
THERMOPHOTOVOLTAIC GENERATOR

JX Crystals Inc

10" O.D. x 24" tall

asttr99a.dwg

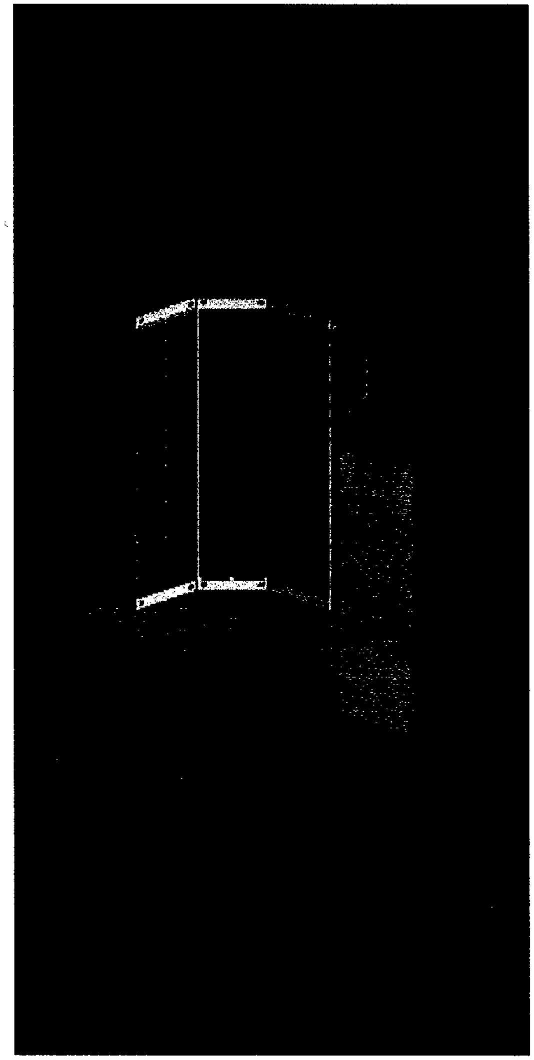
- Photovoltaic Converter Array
- Burner / Emitter / Recuperator



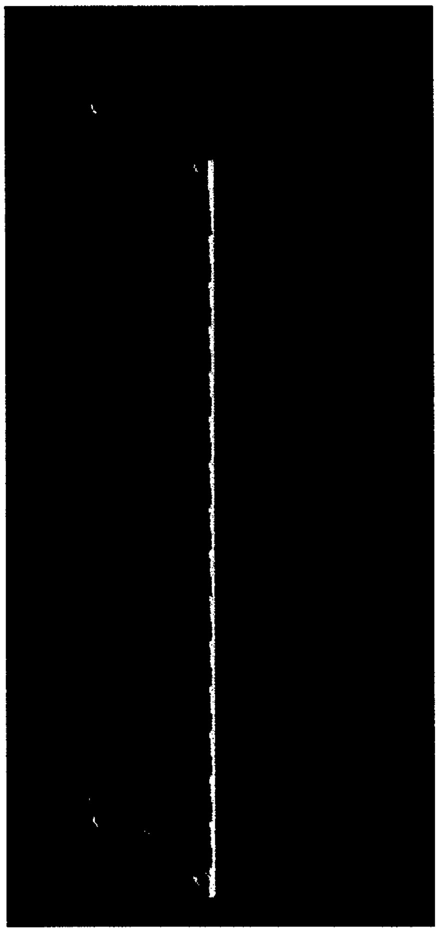
PCA Design

Parts List

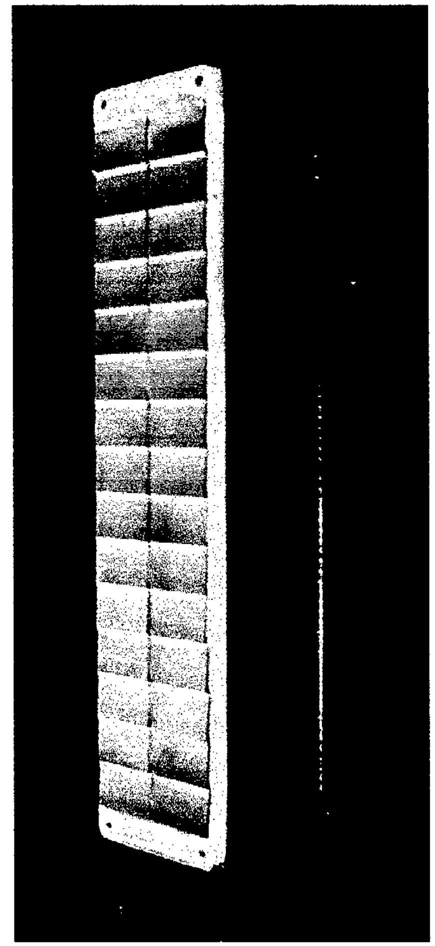
- Circuits with GaSb cells
- Cooling fins
- Interconnect wiring
- Cooling fan
- Fan cowling
- Top hex plate
- Bottom hex plate
- Funnel Pockets
- Support Structure



Circuit & Receiver



GaSb TPV Circuits with Cells, Substrates, & Cooling Fins



PCA #1 Circuit Flash Test Summary

Date	ID1	ID2	FF	Voc	Isc	Imax	Vmax	Pmax	Light
3/12/99	Manual	0 final	0.643	7.07	10.46	8.92	5.33	47.51	0.735
3/12/99	Manual	17 final	0.586	6.94	9.80	7.77	5.14	39.91	0.736
3/12/99	p&p_lines	1 final	0.670	6.98	9.89	8.74	5.29	46.28	0.736
3/12/99	p&p_lines	2 final	0.626	7.13	9.79	8.35	5.23	43.68	0.727
3/12/99	p&p_lines	3 final	0.662	7.30	9.80	8.54	5.54	47.30	0.729
3/12/99	p&p_lines	4 final	0.531	6.89	9.95	8.00	4.54	36.38	0.736
3/12/99	p&p_dots	6 final	0.586	6.79	10.11	8.19	4.91	40.23	0.738
3/12/99	p&p_dots	7 final	0.614	6.75	9.81	8.48	4.79	40.65	0.739
3/12/99	p&p_lines	9 final	0.578	6.71	9.47	7.94	4.62	36.67	0.736
3/12/99	p&p_dots	10 final	0.674	7.02	9.68	8.61	5.32	45.77	0.735
3/12/99	p&p_dots	11 final	0.654	6.92	9.74	8.38	5.26	44.05	0.736
3/12/99	p&p_dots	12 final	0.539	7.03	9.65	7.25	5.04	36.56	0.734
3/12/99	p&p_dots	13 final	0.671	6.99	9.43	8.36	5.29	44.26	0.735
3/12/99	p&p_dots	14 final	0.625	7.14	9.60	8.20	5.22	42.82	0.733
		Average	**0.619**	**6.98**	**9.80**	**8.27**	**5.11**	**42.29**	**0.735**

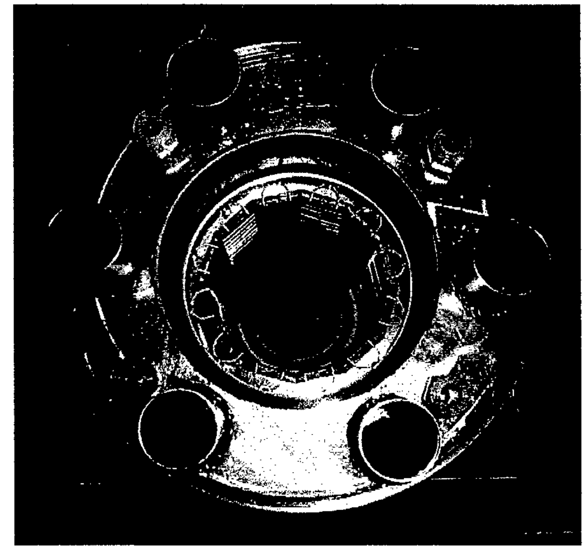
PCA #2 Circuit Flash Test Summary

##	Date	ID2	ID2	FF	Voc	Isc	Imax	Vmax	Pmax	Light
1	4/19/99	Filter	15 final	0.701	6.67	4.49	3.89	5.40	21.01	0.377
2	4/19/99	Filter	16 final	0.717	6.70	4.62	4.19	5.29	22.17	0.383
3	4/19/99	Filter	17 final	0.688	7.01	4.60	3.93	5.64	22.14	0.378
4	4/19/99	Filter	18 final	0.680	6.65	4.60	4.00	5.20	20.78	0.380
5	4/19/99	Filter	19 final	0.683	6.97	4.81	4.07	5.64	22.91	0.381
6	4/19/99	Filter	20 final	0.704	7.02	4.71	4.03	5.78	23.28	0.379
7	4/19/99	Filter	21 final	0.717	7.13	4.73	4.23	5.71	24.16	0.385
8	4/19/99	Filter	22 final	0.685	7.01	4.54	3.96	5.52	21.84	0.381
9	4/19/99	Filter	24 final	0.686	6.99	4.64	4.06	5.48	22.26	0.383
10	4/19/99	Filter	25 final	0.697	6.96	4.52	4.03	5.45	21.93	0.383
11	4/19/99	Filter	26 final	0.691	6.95	4.50	3.97	5.45	21.60	0.384
12	4/19/99	Filter	27 final	0.708	6.94	4.74	4.14	5.62	23.29	0.380
			Average:	**0.696**	**6.92**	**4.63**	**4.04**	**5.52**	**22.28**	**0.381**

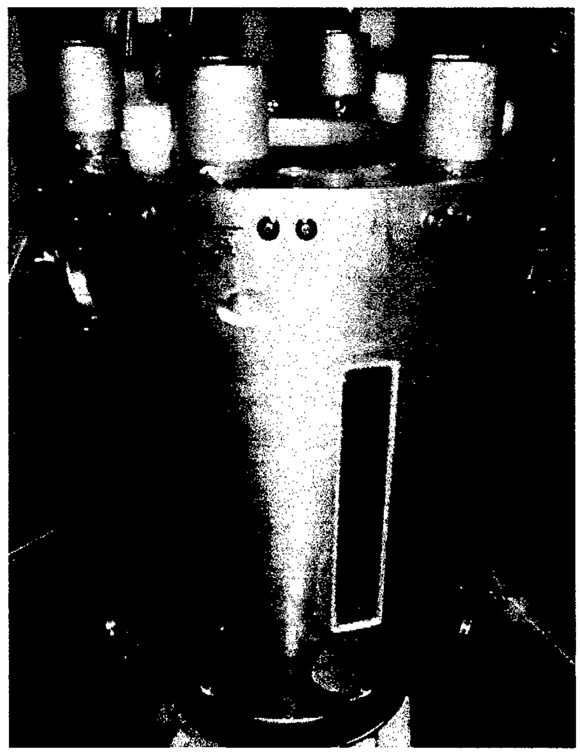
PCA #3 Circuit Flash Test Summary

Date	ID1	ID2	FF	Voc	Isc	Imax	Vmax	Pmax	Light
6/14/99	NF	5 final	0.681	6.36	4.71	4.12	4.95	20.39	0.413
6/14/99	NF	28 final	0.705	6.60	4.55	3.96	5.34	21.17	0.415
6/14/99	NF	29 final	0.720	6.93	4.55	4.08	5.57	22.69	0.415
6/14/99	NF	30 final	0.687	6.89	4.53	3.98	5.39	21.44	0.416
6/14/99	NF	31 final	0.700	6.50	4.70	4.15	5.15	21.38	0.410
6/14/99	NF	32 final	0.702	6.93	4.59	4.09	5.46	22.31	0.409
6/14/99	NF	33 final	0.722	6.89	4.41	3.94	5.57	21.95	0.413
6/14/99	NF	34 final	0.707	6.51	4.50	3.98	5.20	20.69	0.414
6/14/99	NF	35 final	0.710	6.52	4.38	3.93	5.16	20.29	0.415
6/14/99	NF	36 final	0.668	6.85	4.55	4.03	5.17	20.84	0.415
6/14/99	NF	37 final	0.661	6.80	4.59	4.13	5.00	20.64	0.413
6/14/99	NF	38 final	0.678	6.81	4.69	4.04	5.35	21.62	0.409
6/14/99	NF	39 final	0.692	6.79	4.64	4.19	5.21	21.80	0.408
6/14/99	NF	40 final	0.662	6.59	4.57	4.03	4.94	19.92	0.410
		Average:	**0.693**	**6.71**	**4.57**	**4.05**	**5.25**	**21.22**	**0.413**

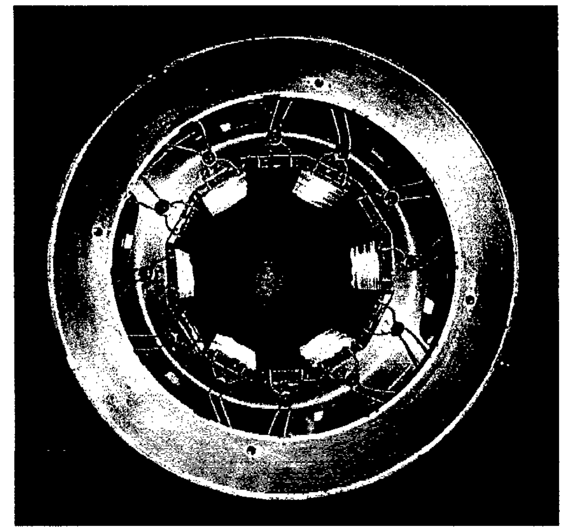
PCA #1



Pictured in Globar Test Configuration

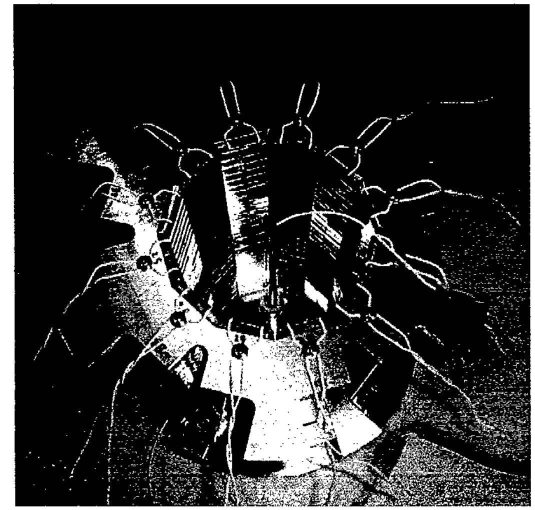


PCA #2

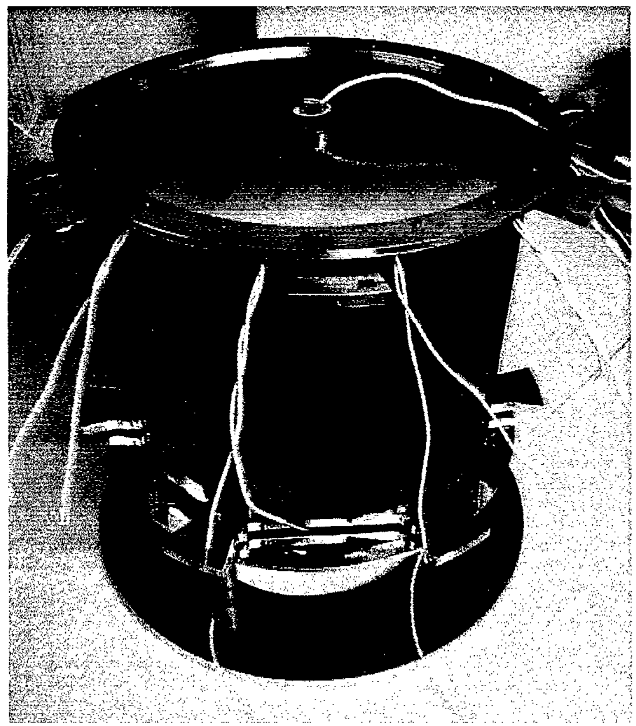


Pictured in Burner Test Configuration

PCA #3



Pictured in Tungsten Lamp Test Configuration



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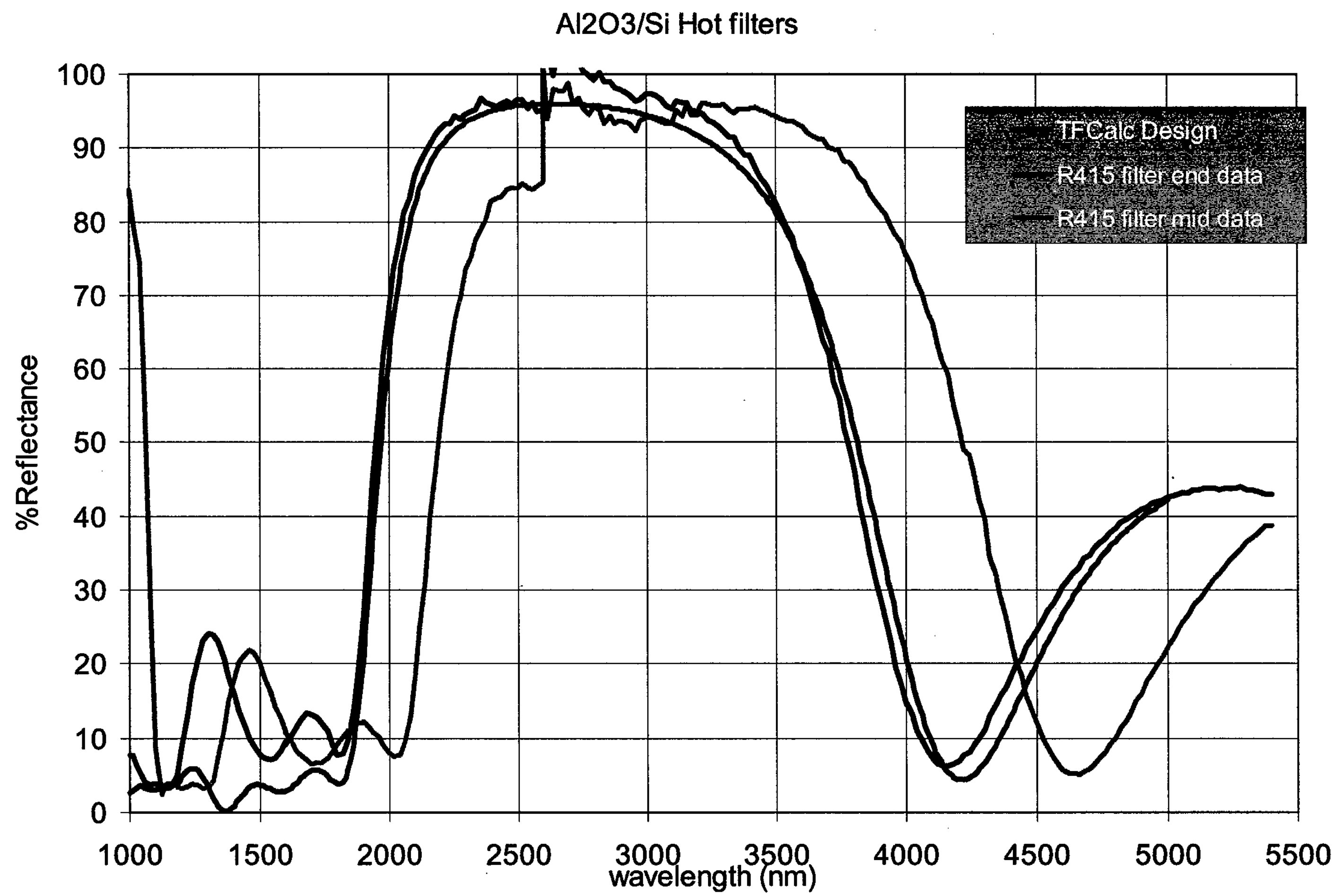
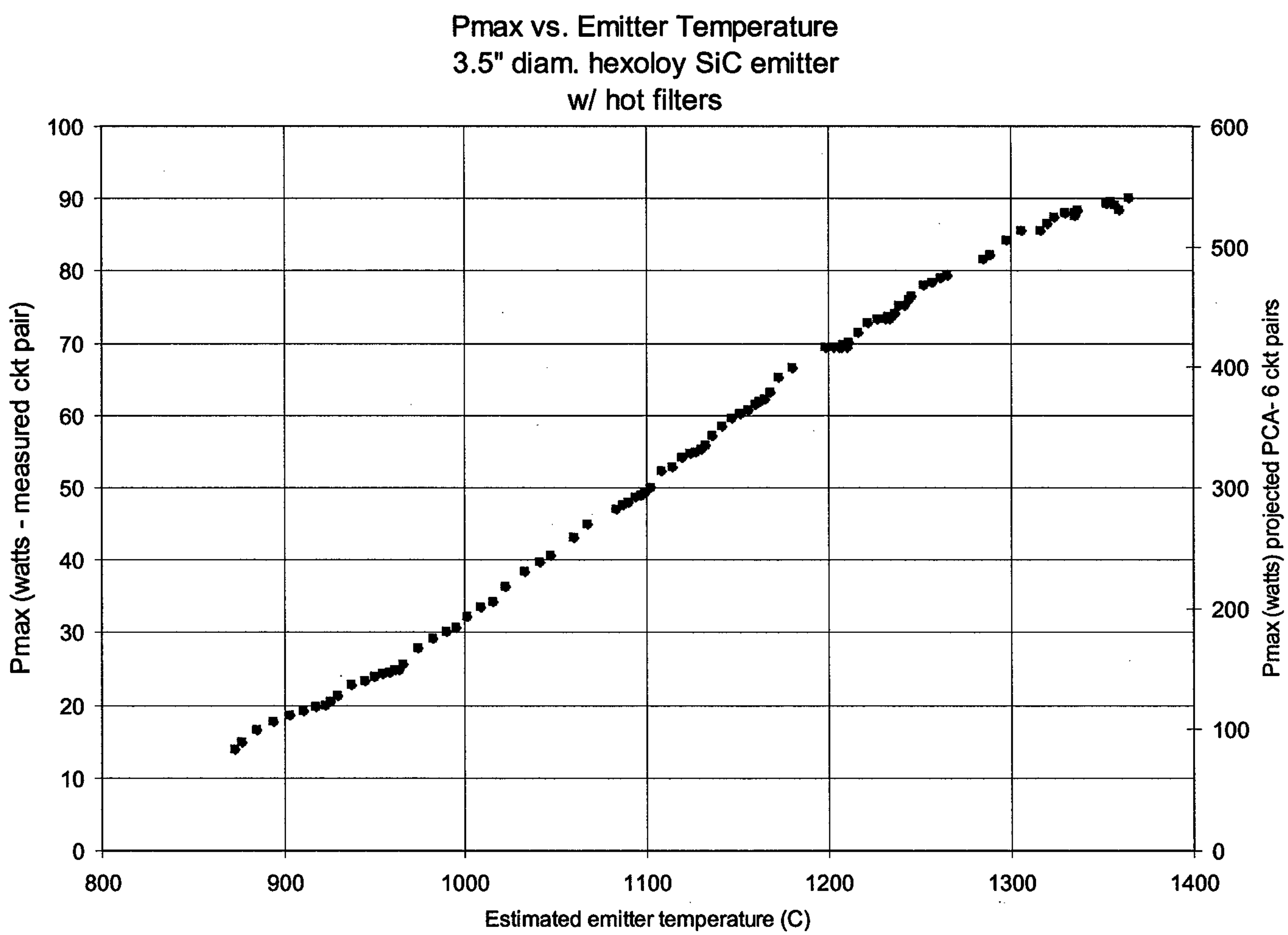
Filter Design & Spectra



Globar Test Data for Hot Filters

		12b *globar only no hot filters*	13a *globar only w/ hot filters*	23 *globar only no hot filters w/ flow diverter*	12b *globar only no hot filters*	13a *globar only w/ hot filters*	23 *globar only no hot filters w/ flow diverter*
$T_{globar\ avg}$	(C)	1154	1155	1155	1170	1171	1183
P_{max}	(watts)	41.7	38.7	35.7	41.7	39.5	36.6
FF		0.62	0.67	0.62	0.62	0.64	0.61
I_{sc}	(amperes)	6.01	4.86	5.10	6.01	5.22	5.53
V_{oc}	(volts)	11.1	11.9	11.2	11.1	11.8	10.9
$T_{ckt\ 1}$ *top*	(C)	85.1	56.4	55.9	88.3	57.6	62.8
$T_{ckt\ 2}$	(C)	58.1	39.1	53.1	59.7	39.9	60.9
$T_{ckt\ 3}$	(C)	53.9	41.7	58.4	55.0	42.4	67.6
$T_{ckt\ 4}$	(C)	58.8	42.5	56.7	59.9	42.9	66.4
$T_{ckt\ 5}$ *bottom*	(C)	64.4	47.1	59.9	66.1	47.8	70.3
P_{in}	(watts)	8770	7520	7520	8711	7539	7383
P_{totalr}	(watts)	6278	4299	5764	6610	4618	5459

PCA#1 Globar Test - 540 Watts



Globar Test with Tungsten Emitter

Goals:

We want to measure a PCA after array wiring & before burner system test. We also want to measure array efficiency given a tungsten emitter in vacuum with a glass envelope.

Test configuration:

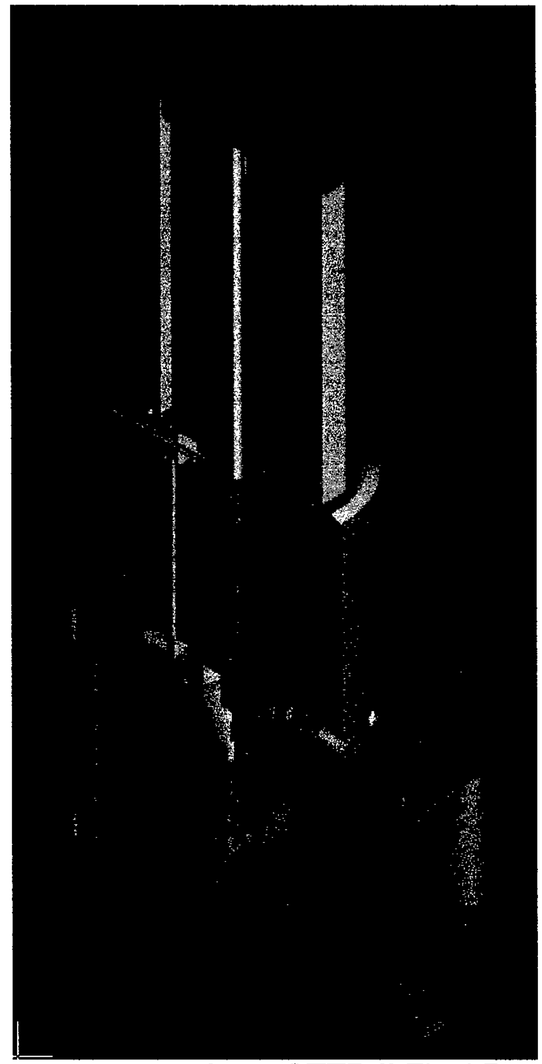
We mounted a 9” long by 0.4” diameter linear infrared bulb with a 6” long tungsten filament coil on the center axis of our PCA. The bulb ends stuck through “ever-bright” aluminum reflecting discs at the ends of the 7” long PCA cylinder.

Result:

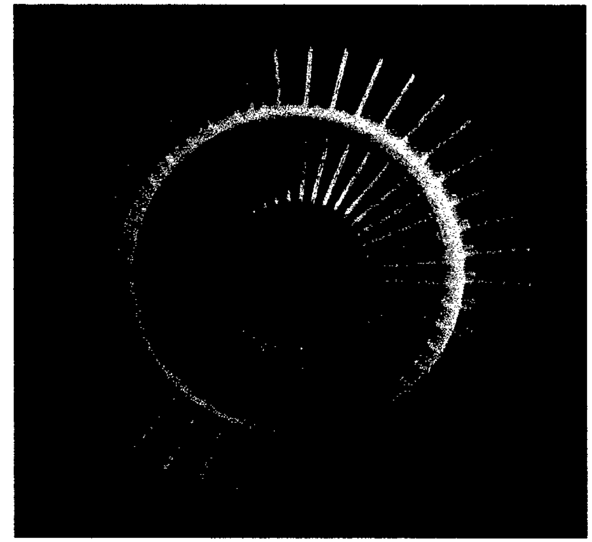
For a lamp input power of 1.1 kW, the array output power was 18 W x 6 = 108 W. This serves to qualify the array wiring. **More importantly, this gives a PCA conversion efficiency of 10%.**

BER Design

Burner Base Plate
Inconel Heat Xchanger
SiC Emitter
Low OH Quartz Shield
SiC Radiator Tube
Blower Adaptor
SALI Emitter Top
Bottom Baseplate
Base Standoffs
Ignitor Tube
Blower
SALI Shell
Burner Injector Base
Burner Jet Shim
Burner Top
Burner Tube
Bottom Fuel Tube
Alumina SALI Shell
Aluminum SALI Shell
ZrPO4 Top Adaptor
ZrPO4 Alumina Support Ring

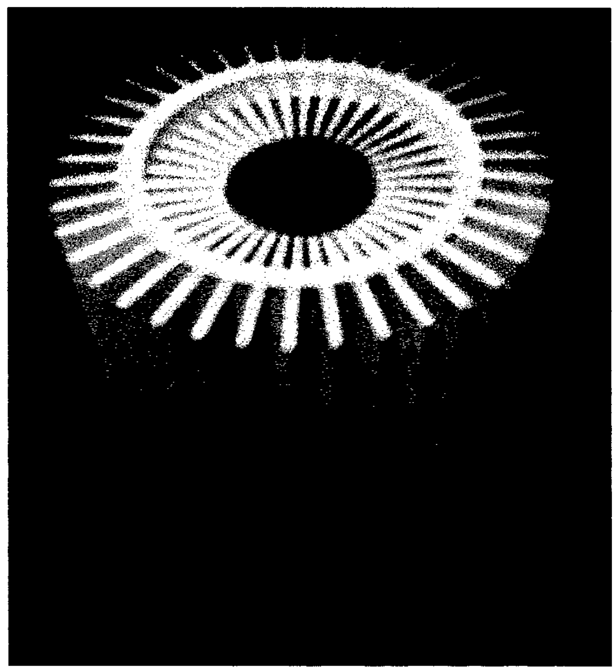


Inconel Recuperator

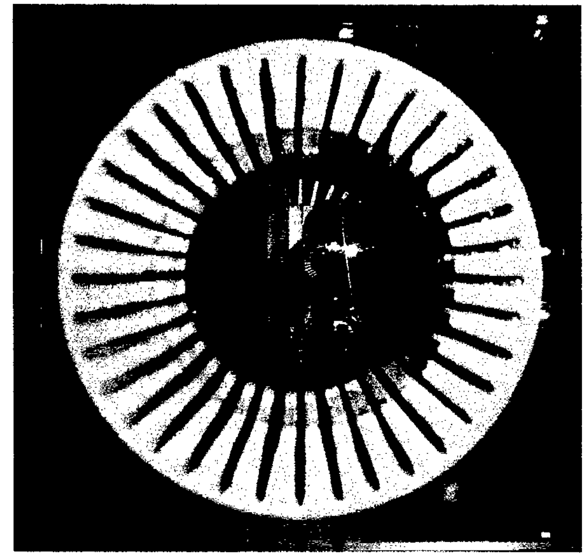


4.5" Tall 3.5" O.D.

Fabricated with wire EDM at WWU

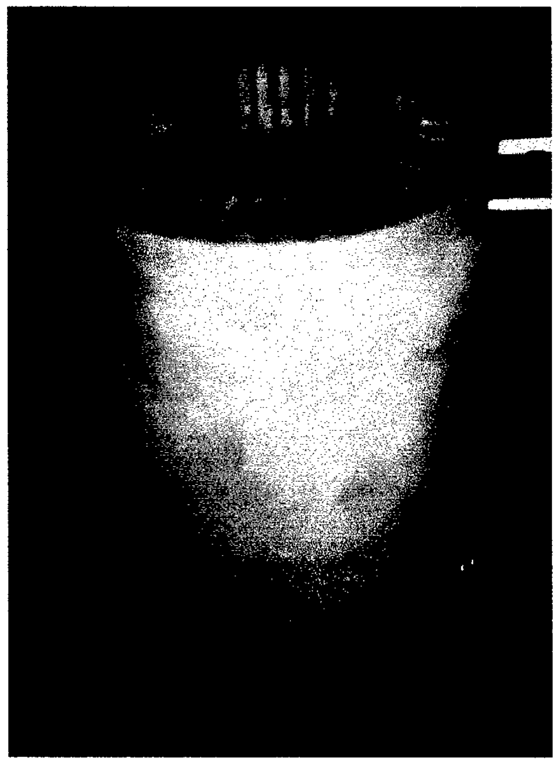


SiC Finned Emitter



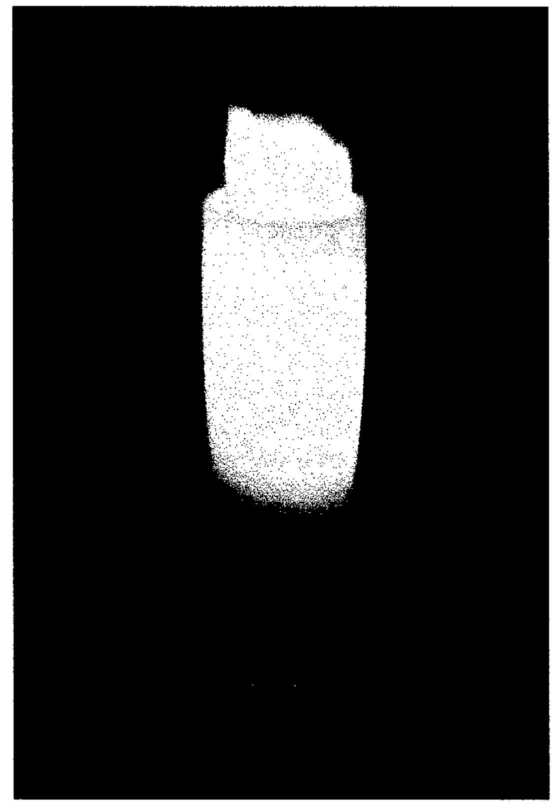
7.5" Tall 3.66" O.D.

Supplied by Coors

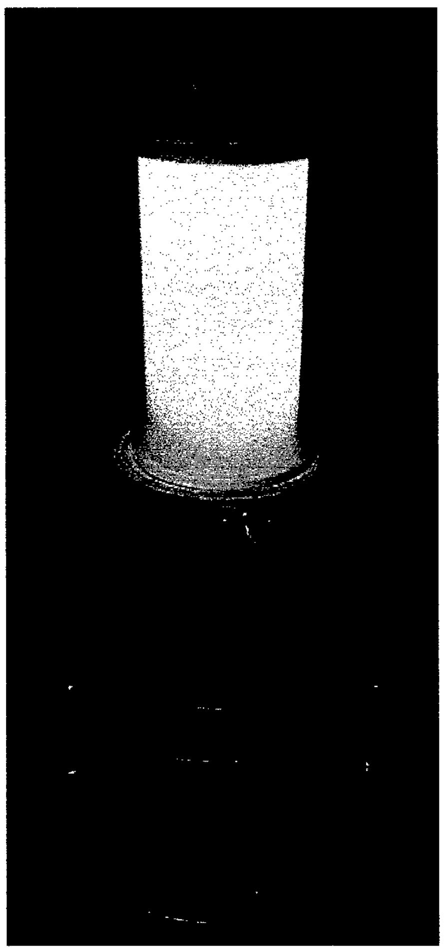


Burner Flame Uniformity

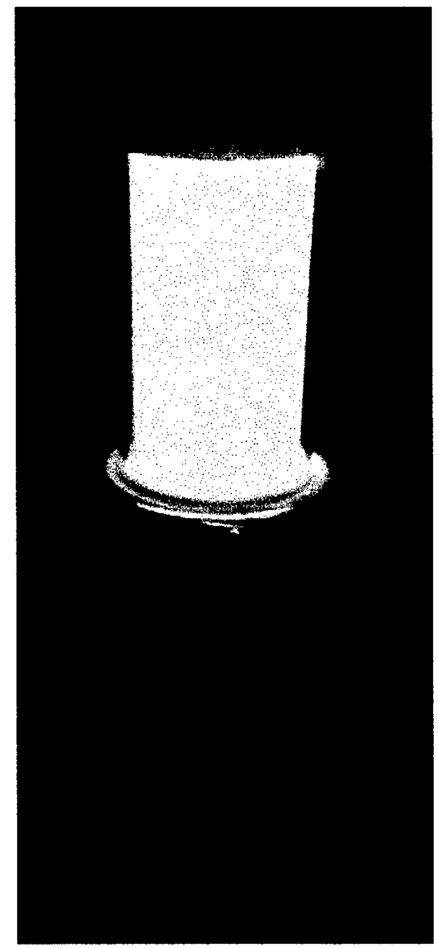
- Swirl of flame provides greater area for enegy transfer
- Eliminating large gradients expands critical component lifespans
- Uniformity increases Fill Factor
- Higher Fill Factors yield higher efficiencies



Burner-Emitter-Recuperator (BER)



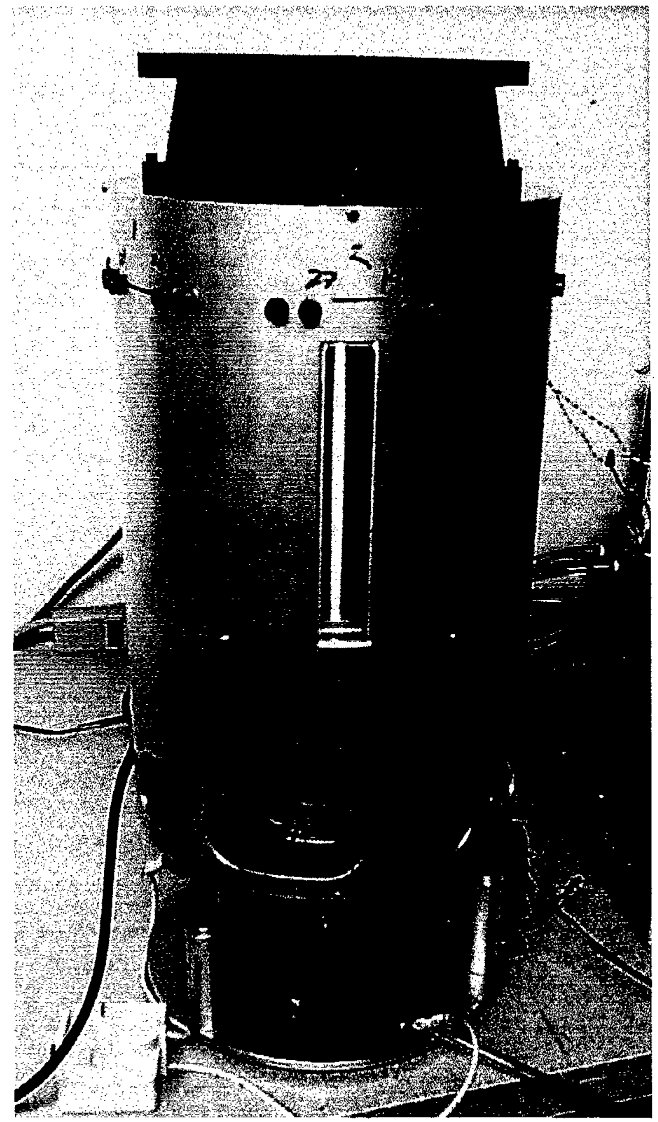
Operating with 6 LPM of propane & combustion air blower



Complete System

1st Iteration of

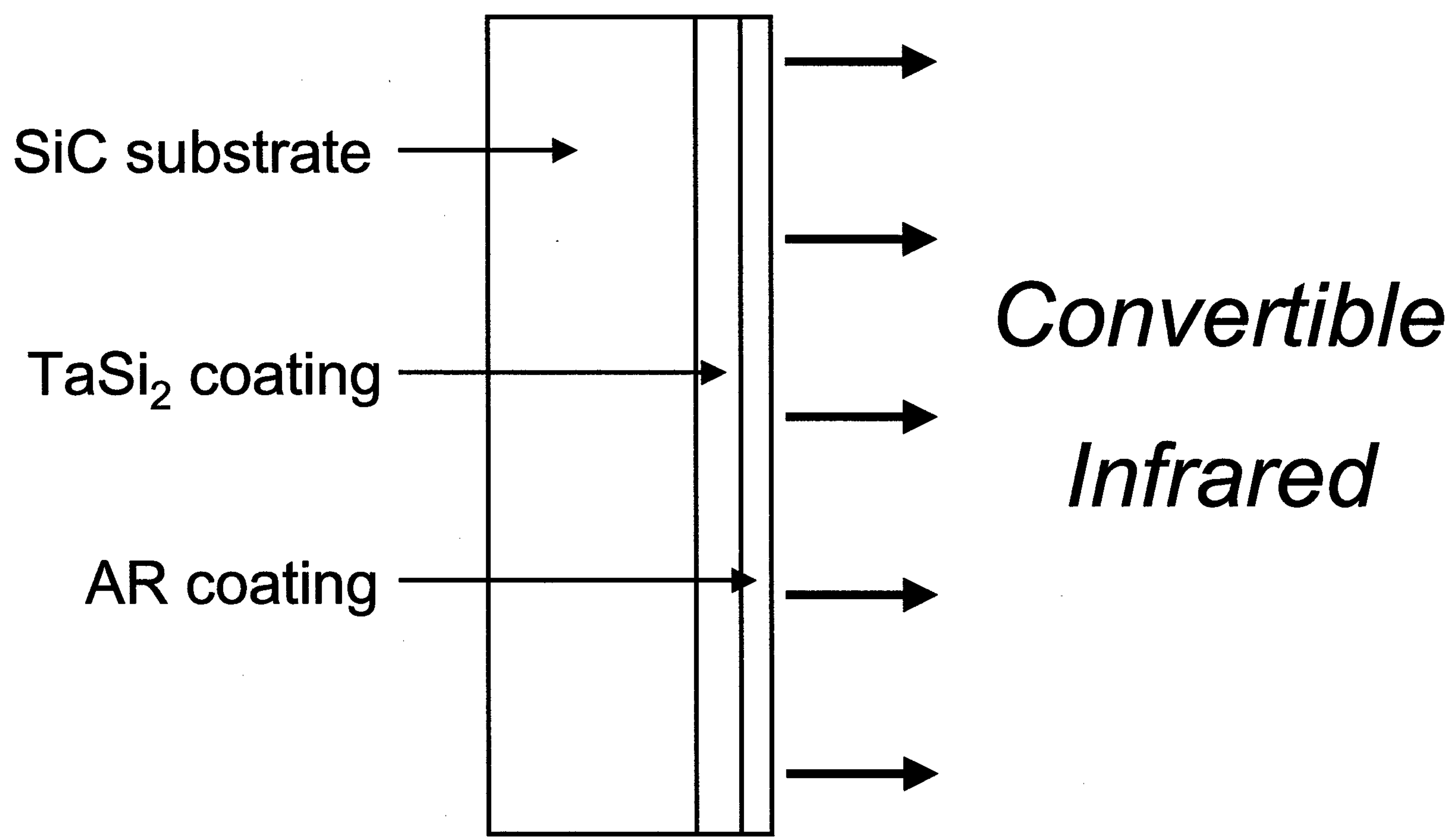
complete TPV Cylinder



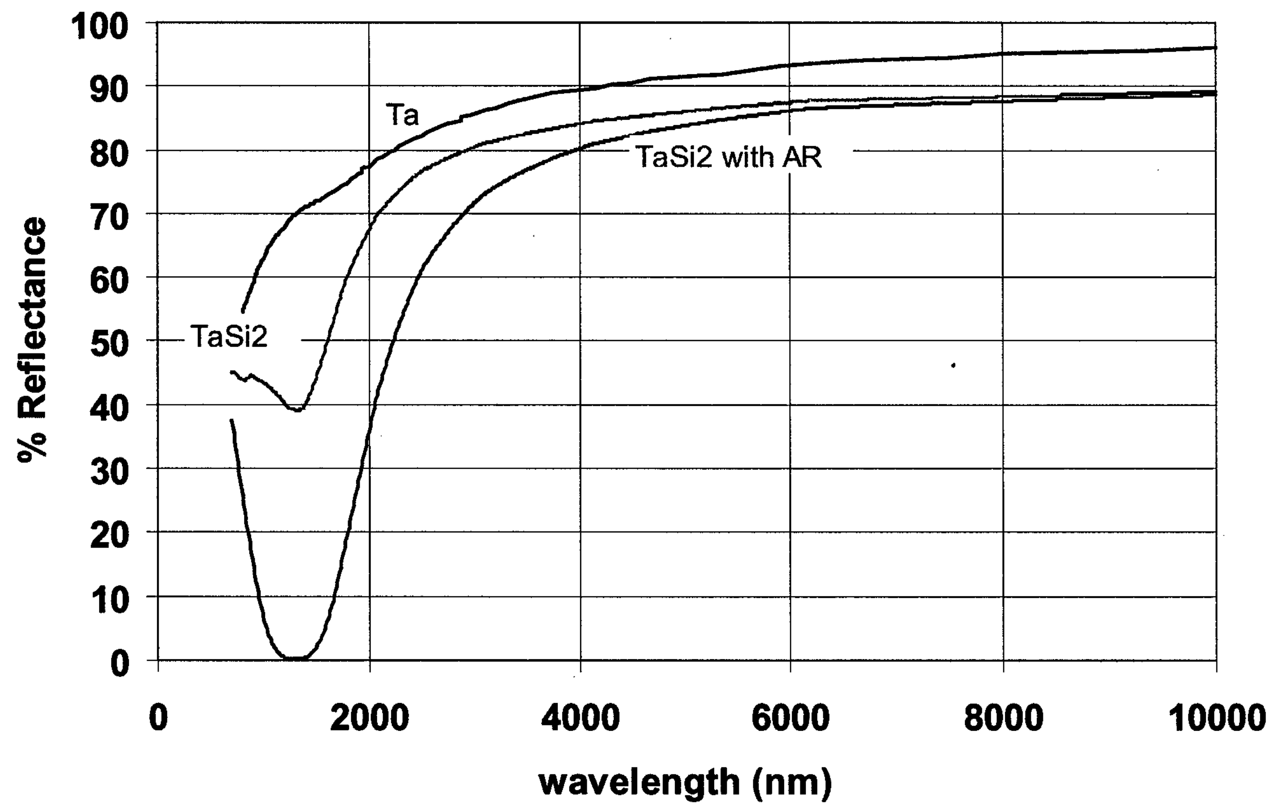
Summary of System Performance

	ASTTR	McDermott
Fuel	1.5 lbs/hr propane	1.5 lbs/hr diesel
Combustion Air	25 W Blower	Compressed Air
Cooling Air	200 cfm, 36 W Fan	340 cfm " "
Emitter Temperature		
Top	1132 C	1180 C
Middle	1225 C	1140 C
Bottom	1142 C	1130 C
Circuit Temperature	85 to 95 C	70 to 80 C
Array Output		
Isc	4.0 A	4.6 A
Voc	10.4 V	10.2 V
FF	0.54	0.60
Pmax	22.5 W x 6 = 135 W	27 W x 6 = 162 W

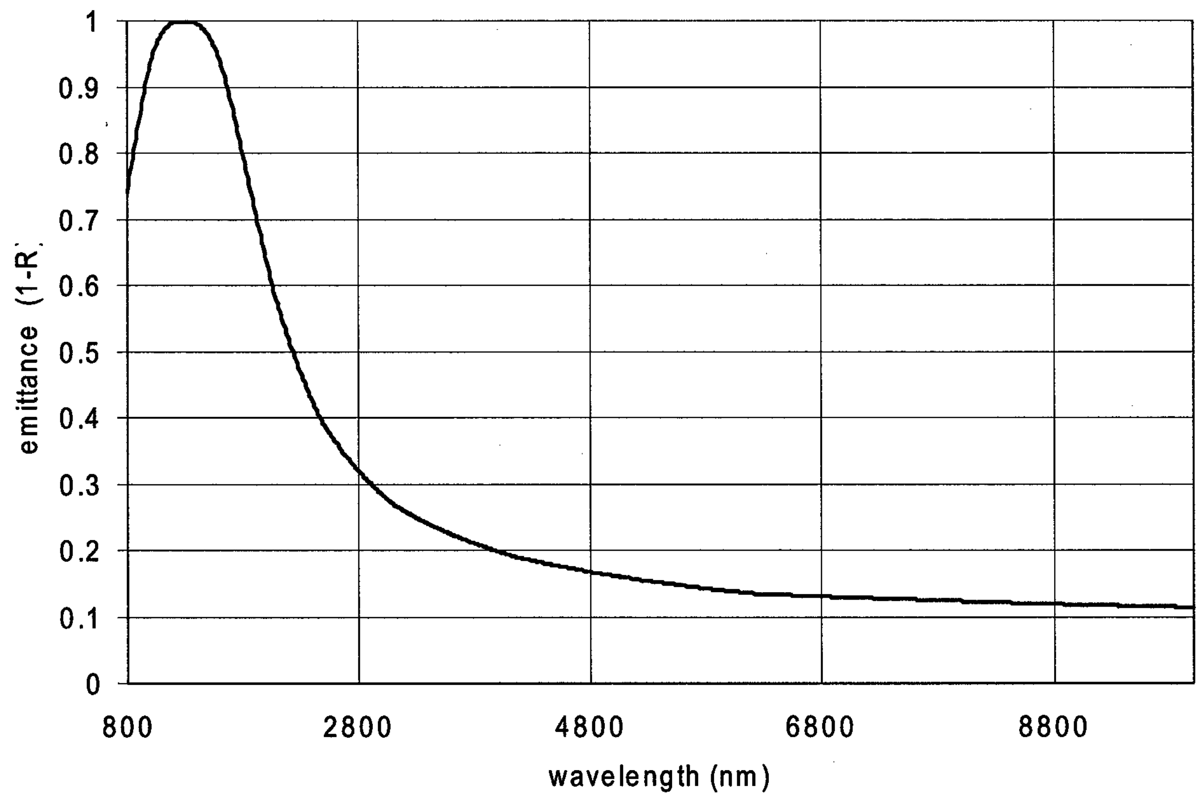
AR-coated silicide emitter concept



Theoretical reflectance (1 - theoretical emittance)

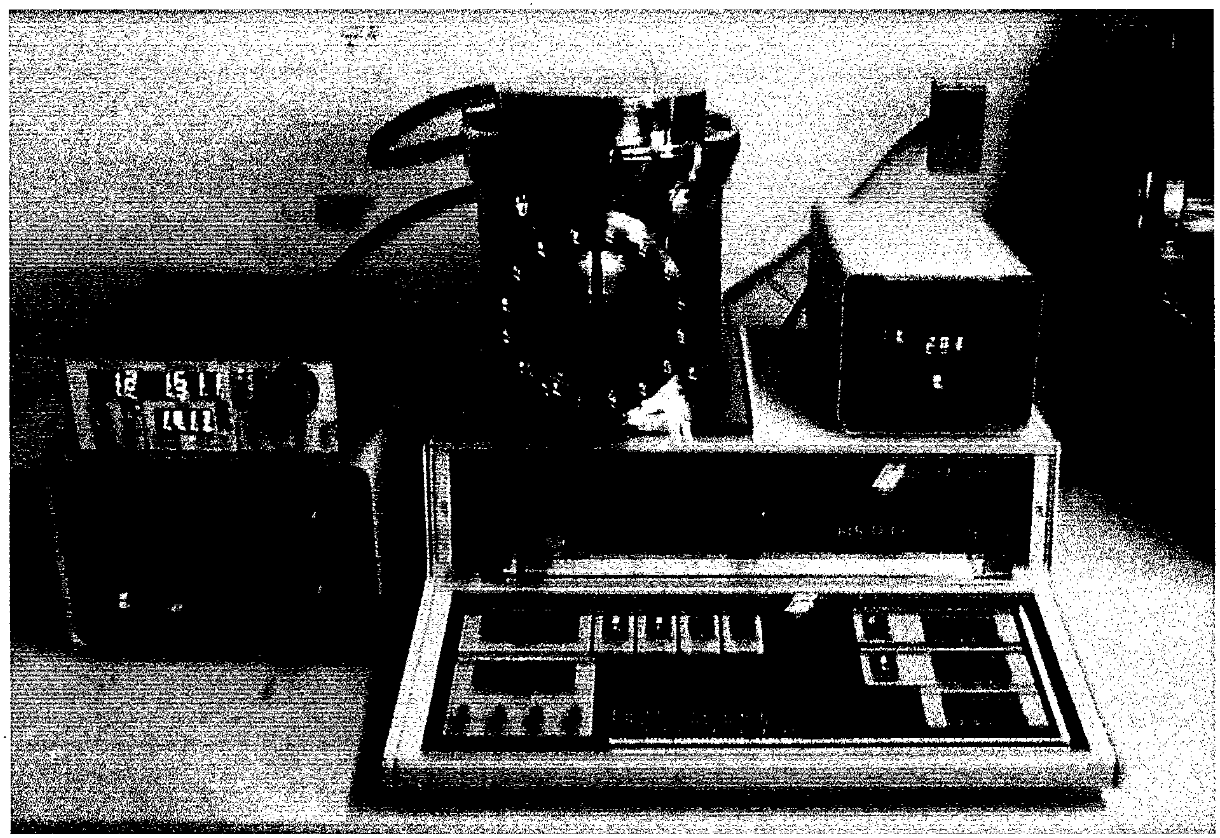


Theoretical emittance Anti-reflective coating on $TaSi_2$

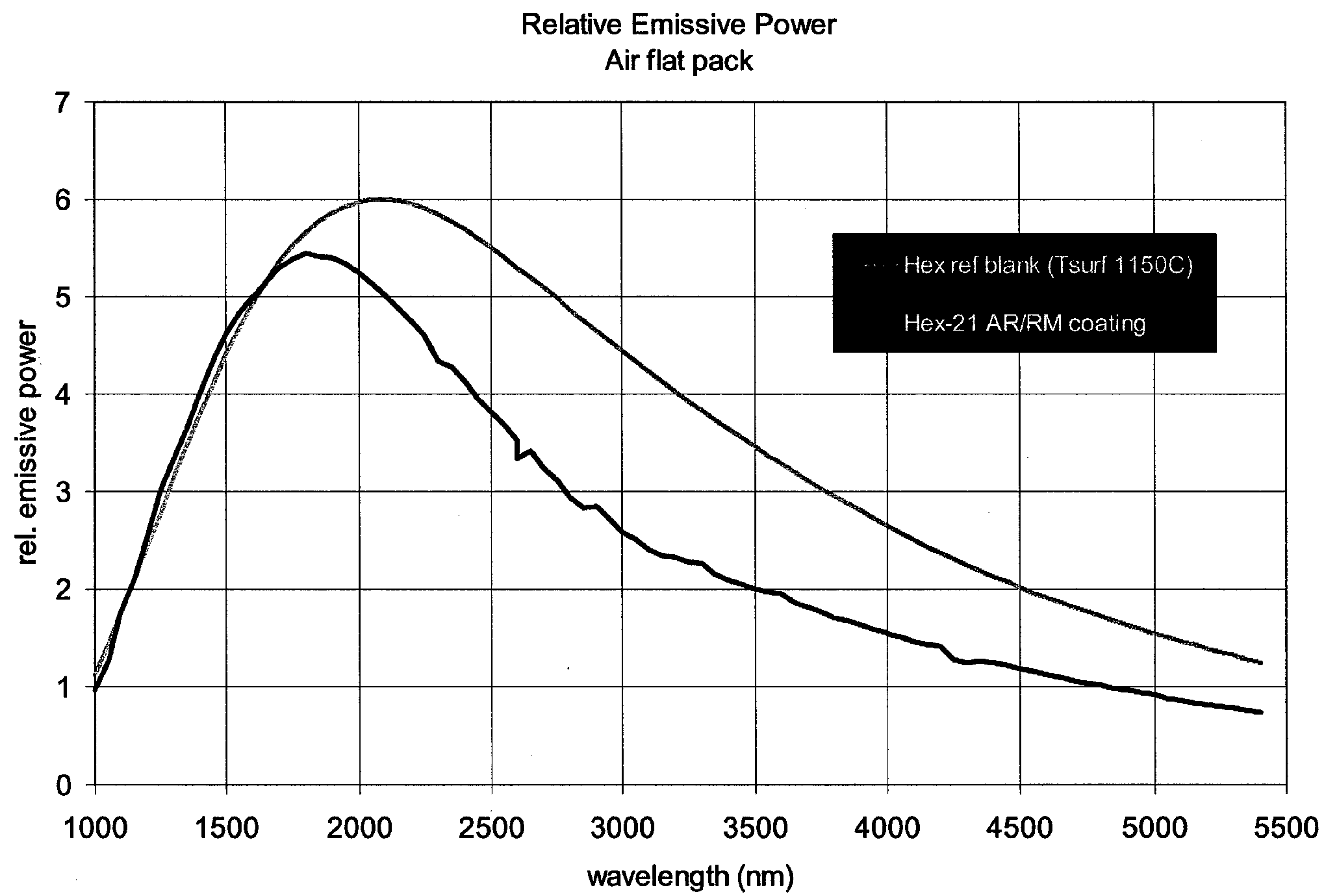


Sputtering System

Newly acquired R&D sputtering system used for coating emitter coupons

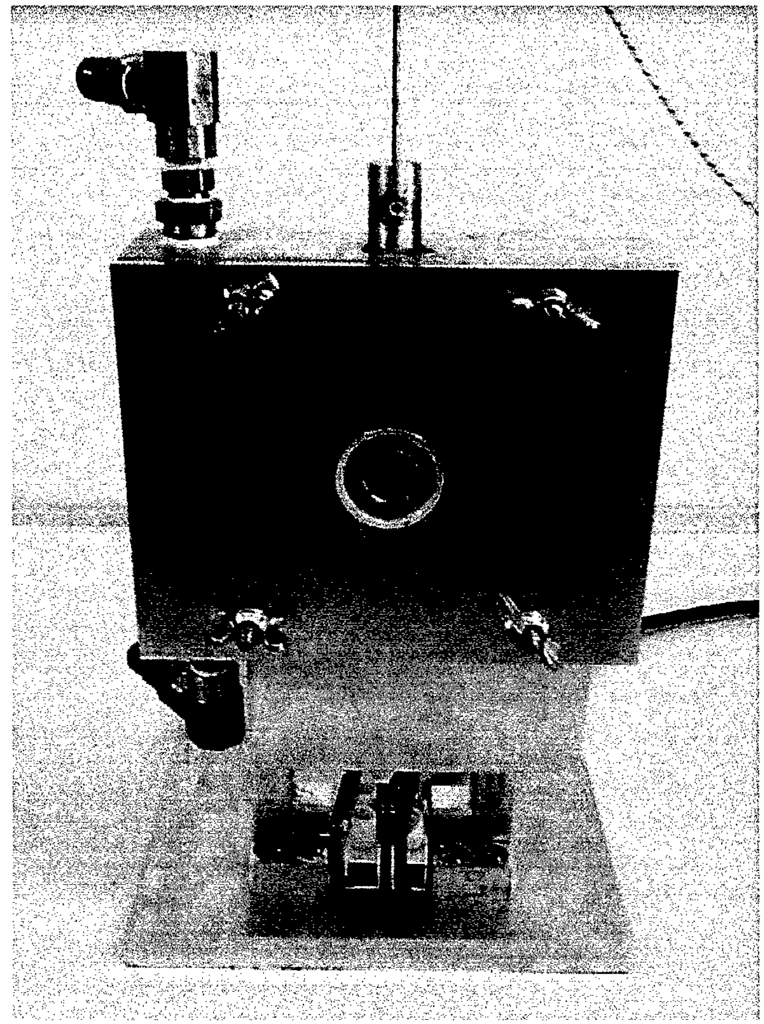


Measurement of Emitter Spectra



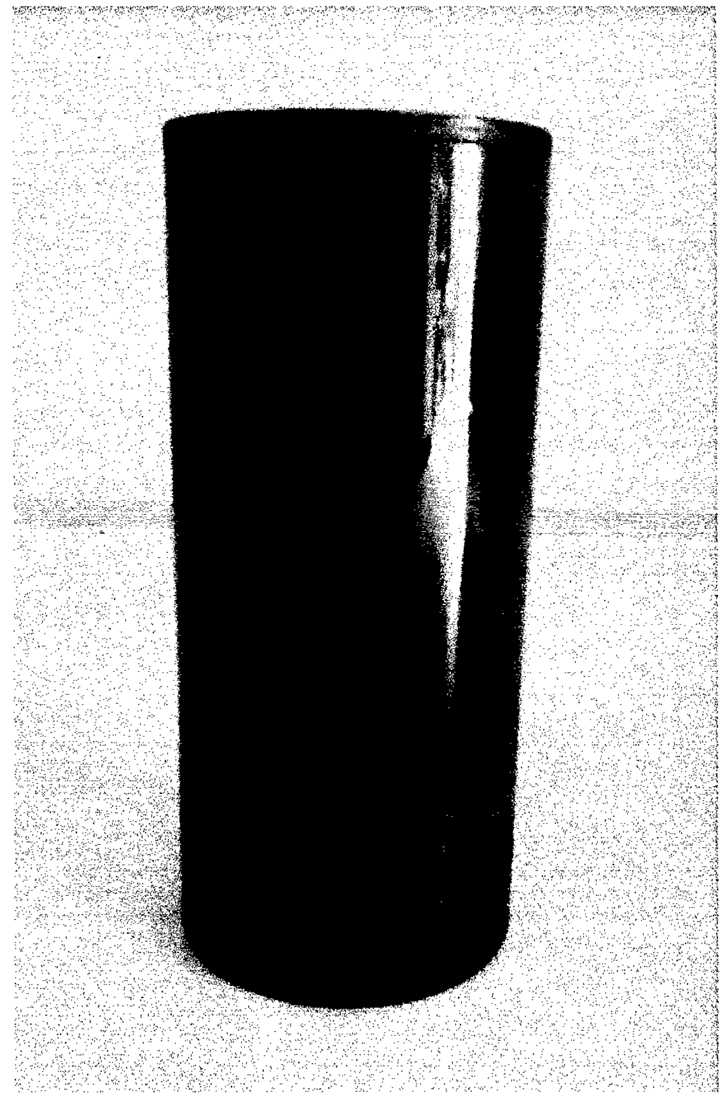
Vacuum FlatPack

JXC Vacuum FlatPack used for emittance measurements



Coated Cylinder

JXC coated cylinder using new rotisserie in e-beam evaporator



Summary of Accomplishments

Task	Status
1. Cell and circuit design and optimization	1200 cells and 40 circuits completed
2. PCA design, fabrication, and optimization	3 PCAs fabed; 540 W PCA demonstrated
3. Cooling system design and optimization	200 cfm fan for PCA cooling demonstrated
4. Propane burner design and fabrication	5 lpm, Jet shim disc, & swirler demonstrated
5. Recuperator design, fabrication, and testing	Finned inconel recuperator EDM fabed at WWU
6. Emitter and radiator design and fabrication	Procured from Coors and Carborundum
7. Spectral control design & implementation	Dielectric filters fabricated in-house; 10% PCA efficiency demo
8. TPV system design, fabrication, & testing	First iteration completed

Goals Revisited

Design Goals	6/99	Status
Fuel Energy Input 8 kW	8 kW	propane burner demo
Emitter Radiant Output	5.6 kW	70% recuperation demo; PCA cooling demo.
Emitter Temperature	1430 C	Not demonstrated; Need emitter thermos with improved spectral control.
PV Array Output	560 W	540 W PCA demonstrated
Net Output	500 W	Fan & blower power = 60 W
Net Efficiency	6.3%	10% PCA demo with tungsten emitter in evacuated glass tube

THERMOPHOTOVOLTAIC GENERATOR

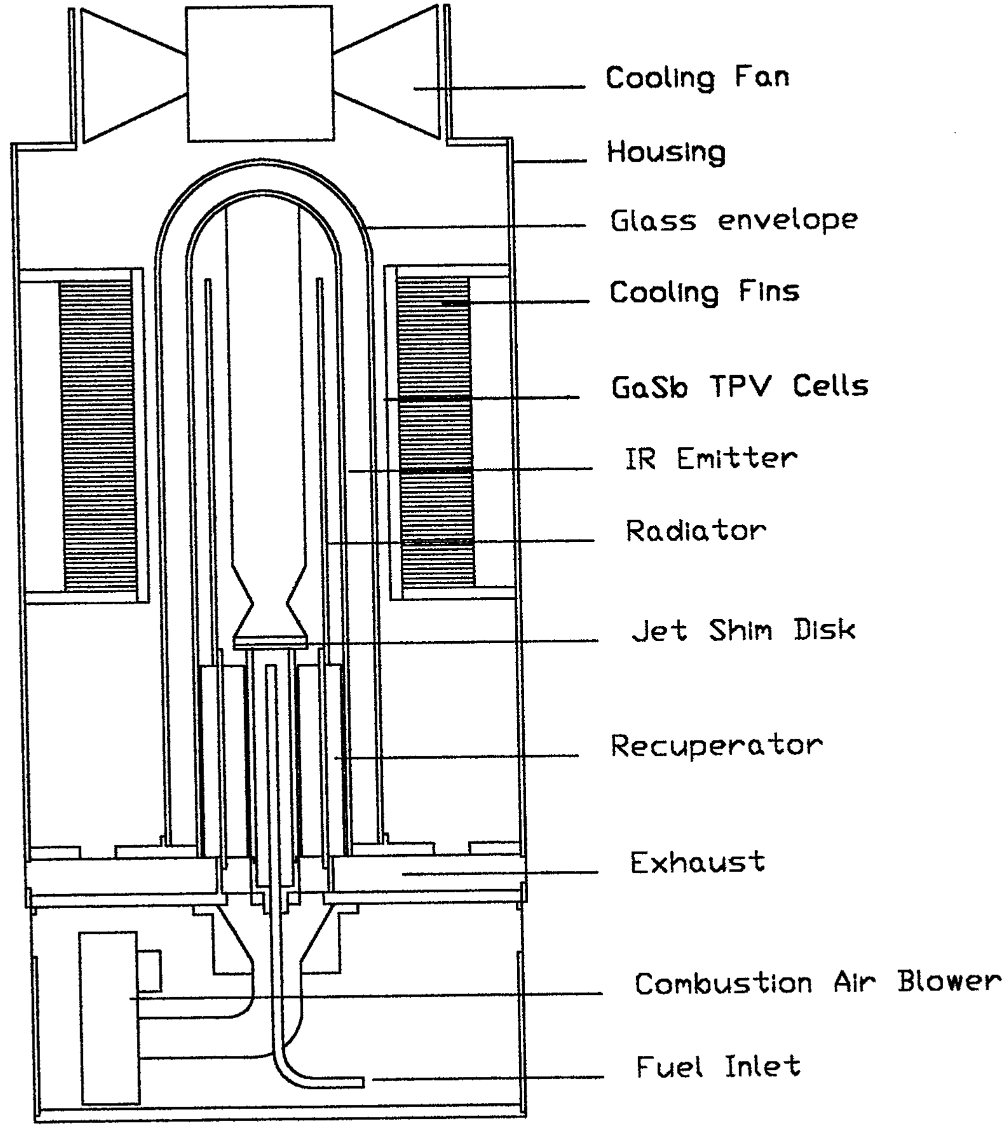
JX Crystals Inc

10" O.D. x 24" tall

asttriii.dwg

▬ Photovoltaic Converter Array

▬ Burner / Emitter / Recuperator



Recommendations for Future Improvements

As a result of this contract, there are now two propane -fired TPV test systems. One is at JXC and the other will be at the Army Fort Monmouth Research Lab.

We recommend that the propane fired TPV systems developed under this contract be used as a test bed for experiments on emitter thermos development as well as diesel fuel burner development.

Specifically, we recommend that both systems be rebuilt to accommodate the new emitter thermos with improved spectral control.

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Using Infrared-Sensitive Gallium Antimonide Cells

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13. ABSTRACT *(Maximum 200 words)*

Three cylindrical thermophotovltaic generators were fabricated under this contract, using gallium antimonide photovoltaic converter arrays. The converter arrays consist of twelve air-cooled circuits each, with each circuit containing thirty cells. The arrays were tested with an electrically heated emitter at 200 cubic feet per minute of air cooling, with the anticipated power output of 150 Watts; at higher air volumes, array output reached 540 Watts. One of the three arrays was fitted for further testing, and the other two were incorporated into propane-fired systems. These propane-fired systems use silicon carbide emitters and are fitted with recuperators to put some of the waste heat back into the combustion process. At one pound of fuel per hour, a system output of 135 Watts was achieved. Management of the heat load on the cells was a limiting factor, with the conclusion that it is critical to limit the amount of non-useful longer wavelength energy being emitted. A way to do that has been identified and is being pursued under separate funding.

14. SUBJECT TERMS
thermophotovoltaic, gallium antimonide, GaSb, infrared

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